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RESEARCH MEMORANDUM

FREE-JET INVESTIGATION OF 20-INCH RAM-JET COMBUSTOR UTILIZING HIGH-HEAT-RELEASE PILOT BURNER

By James G. Henzel, Jr., and Carl B. Wentworth

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

An investigation of the performance of a 20-inch-diameter ram-jet engine utilizing a high-heat-release pilot burner was conducted at zero angle of attack in a free-jet test facility at a Mach number of 3.0. Two flame-holder configurations were utilized in conjunction with the high-heat-release pilot burner over a range of simulated altitudes from 61,700 to 74,400 feet.

The two configurations - one incorporating a flame holder composed of annular V-gutters and the other incorporating a flame holder composed of sloping radial gutters - gave combustor efficiencies of 0.84 and 0.89, respectively, at a fuel-air ratio of 0.02 and about 1100 pounds per square foot combustor pressure.

The high-heat-release pilot burner configuration with the sloping-gutter flame holder had about the same minimum specific fuel consumption (2.2) as a typical small pilot burner configuration of the same over-all engine length. Thus, for these particular configurations it is doubtful that the additional complication introduced by the high-heat-release pilot burner can be justified.

INTRODUCTION

Ram-jet engines used for some long-range missile flight plans, as outlined in reference 1, require combustors capable of operating efficiently over a wide range of fuel-air ratios and pressures. The cruise portion of these flight plans requires efficient operation at fuel-air ratios approximately in the range 0.02 to 0.035. High combustor efficiency at cruise conditions is mandatory because, to a first-order approximation, the range of a missile is proportional to the combustor efficiency. Because of the need for high combustor efficiency at cruise conditions, the investigation reported herein was directed primarily toward the attainment of high combustor efficiency at a fuel-air ratio of about 0.02 without compromising the efficiency at the higher fuel-air ratios. The fuel-air ratio of 0.02 was selected because it is in the range of interest for cruise operation at a flight Mach number of 3.0.

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In an effort to increase the combustor efficiency to higher values than were obtainable in reference 1 (0.78 at fuel-air ratio of 0.02), two flame-holder configurations were investigated which retained the local enrichment features of reference 1; and since information contained in reference 2 indicated that increased heat release from the pilot burner might have beneficial effects on combustion efficiency, these configurations also incorporated high-heat-release central pilot burners. For this investigation, the pilot burner was designed to capture approximately 12 percent of the engine air flow; hence, it is called a "12-percent pilot burner." 3035

The data presented in this report were obtained by operating the 20-inch-diameter ram-jet engine of reference 1 at zero angle of attack in a free-jet test facility. The nominal Mach number of the jet was 3.0 and the range of altitudes simulated in the jet was 61,700 to 74,400 feet. The engine combustor was operated from a fuel-air ratio of about 0.006 to a fuel-air ratio of about 0.08. For these conditions, combustion-chamber-exit total pressures of 740 to 2340 pounds per square foot absolute were obtained. The inlet total temperature was held constant at 1100° R, which is the standard total temperature for a flight Mach number of 3.0 above the tropopause.

APPARATUS

Test Facility

The ram-jet engine was mounted in a free-jet facility which is shown schematically in figure 1. Air entered the facility through a combustion-type preheater. The hot exhaust gases of the preheater contaminated the air to a fuel-air ratio of 0.009 or less. The air then passed into a surge tank and was expanded through a convergent-divergent nozzle to a Mach number of 3.0. The engine diffuser inlet was submerged in the Mach number 3.0 jet and the excess air spilled around the engine inlet through the jet diffuser. The engine exhaust passed into a separate chamber which could be throttled for engine starts. A complete description of the free-jet test facility and its operation is given in reference 3.

Engine

A schematic sketch of the 20-inch-diameter ram-jet engine is shown in figure 2. The inlet diffuser was of the double-cone annular type which utilizes two oblique shocks and one normal shock. The subsonic diffuser portion was divided into three channels by the inner body supports, which extended downstream to the end of the inner body. The combustion chamber, which was water-jacketed, had an inside diameter of 20 inches. For the major portion of the investigation, the engine was

equipped with a contoured water-jacketed convergent exhaust nozzle having a minimum area equal to 55 percent of the combustion-chamber area. A 45-percent nozzle was used to permit the determination of the performance of the pilot burner alone. The pilot burner was ignited by means of a propane-air ignitor. The fuel used in the preheater, ram-jet engine, and pilot burner was MIL-F-5624A, grade JP-4.

Combustion-Chamber Configurations

Two configurations were investigated in the evaluation of the high-heat-release pilot burner as applied to the 20-inch ram-jet engine. The pertinent features of each configuration are summarized in the following table, and each is described in the succeeding paragraphs:

Configuration	Percent pilot burner	Flame holder	Effective combustion-chamber length, in.	Pilot-burner fuel-injection system	Inner-zone fuel-injection system	Outer-zone fuel-injection system
1	12	Annular V-gutter	54.5	Ring with sixteen 0.021-inch holes	See fig. 4	16 spray bars with two 0.040-inch holes each
2	12	Sloping gutter	54.5	Ring with sixteen 0.021-inch holes	16 spray bars with four 0.021-inch holes each	16 spray bars with two 0.040-inch holes each

<u>Configuration 1</u>. - Details of the piloted annular V-gutter combustor are shown in figure 3.

Pilot-burner system: The pilot burner consisted of a modified turbojet burner liner $25\frac{1}{2}$ inches long and 8 inches in diameter. The upstream end of the burner liner, which contained primary-air louvers, was removed so that the burner liner could be mounted on the downstream end of the center body. The fuel-air mixture entered the pilot burner through

eight equally spaced longitudinal rows of 3/4-inch diameter holes and a series of louvers on the burner surface. The cross-sectional area of the combustion zone varied from approximately 0.282 square foot at the plane of the first circumferential row of air holes to 0.328 square foot at the plane of the final circumferential row of holes. A pilot fuel-mixing control sleeve was installed which consisted of a truncated cone that changed in diameter from 10.8 inches at the upstream end to 8.1 inches at the plane of the leading edge of the flame-holder gutters. The pilot burner fuel was sprayed inward from a ring mounted flush with the leading edge of the pilot-burner sleeve. The fuel was confined within the 3035
sleeve, thus permitting separate control of the fuel-air mixture within the pilot burner.

Main-stream fuel-injection system: Configuration 1 had separate outer- and inner-zone fuel-injection systems as shown in figure 3. Each zone used spray bars for fuel injection. The outer-zone fuel-spray bars were located 17.3 inches upstream of the flame holder. The inner-zone fuel-spray bars were located 19.4 inches upstream of the flame holder. The outer-zone fuel-spray bars had a single pair of holes spraying circumferentially. The holes were located approximately midway between the main-stream fuel-mixing control sleeve and the outer combustor wall. Four different inner-zone fuel-spray-bar hole distributions were investigated in an attempt to optimize the fuel-distribution system at a fuel-air ratio of 0.02. The details of each system are given in the following table and are shown in figure 4.

Fuel-distribution system	Number of inner manifold spray bars	Number of holes per inner manifold spray bar	Size of holes in inner manifold spray bar, in.	Direction of fuel sprays
a	16	2	0.0292	Circumferential
b	32	2	.0292	Circumferential
c	32	2	.0310	Upstream
d	16	4	.0210	Circumferential

Flame holder: The flame holder for configuration 1 (fig. 3) consisted of nine radial and two annular V-gutters. Three large radial gutters extended from the pilot-burner discharge and were 2.2 inches wide at the open end. The two annular V-gutters were 1.3 inches wide at the open end and had radii of 6.1 and 8.9 inches. Six small radial gutters 1.3 inches wide extended from the pilot-burner discharge to the

inner annular V-gutter. The total flame-holder blockage including the pilot burner was 60 percent of the combustion-chamber cross-sectional area.

Fuel-mixing control sleeve: The main-stream fuel-mixing control sleeve (fig. 3) consisted of a truncated cone that changed in diameter from 13 inches at the upstream edge to 12.2 inches at the plane of the leading edge of the annular flame-holder gutters. The main-stream fuel-mixing control sleeve was designed to capture approximately 28 percent of the engine air-flow and to confine all the fuel injected by the inner-zone fuel-spray bars between the pilot-burner fuel-mixing control sleeve and the main-stream fuel-mixing control sleeve.

Configuration 2. - Details of the piloted sloping radial gutter combustor are shown in figure 5.

Pilot-burner system: The pilot-burner system for configuration 2 was identical to that utilized for configuration 1.

Main-stream fuel-injection system: Configuration 2 also had separate outer- and inner-zone fuel-injection systems. The outer-zone fuel-injection system for configuration 2 was identical to that used for configuration 1. The inner-zone fuel-injection system for configuration 2 was identical to fuel-distribution system d used for configuration 1.

Flame holder: The sloping-gutter flame holder, shown in the sketch of figure 5 and photographed in figure 6, replaced the annular V-gutter flame holder of configuration 1. This flame holder consisted of two sets of channel-shaped sloping radial gutters interconnected by a conical sleeve section. The inner set consisted of six equally spaced gutters inclined at a 30° angle to the combustor axis. Each gutter of the inner set was $3\frac{7}{16}$ inches long and about 3 inches wide at the open end. The outer set consisted of 12 equally spaced gutters inclined at a 30° angle to the combustor axis. Each gutter of the outer set was $5\frac{3}{4}$ inches long and about $1\frac{1}{2}$ inches wide at the open end.

Fuel-mixing control sleeve: The main-stream fuel-mixing control sleeve for configuration 2 (fig. 5) was similar to that used for configuration 1.

Instrumentation

The locations of temperature and pressure instrumentation at the various stations are shown in figures 1 and 2. The inlet total pressure

and temperature were measured in the surge tank upstream of the supersonic nozzle (fig. 1) and were used in establishing the simulated engine flight conditions. A survey of total and static pressures was made at the downstream end of the subsonic diffuser (fig. 2), and the results were used in calculating burner total-pressure ratio and combustion-chamber-inlet Mach number. For some runs, an additional survey of total and static pressures was made just downstream of the high-heat-release pilot burner so that the air flow through the pilot burner could be computed for cold-flow (nonburning) conditions.

An NACA mixture analyzer similar to that described in reference 4 measured the pilot-burner-discharge fuel-air ratio which was used to determine the air flow through the pilot burner under burning conditions.

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A water-cooled rake (fig. 2) located just upstream of the engine exhaust nozzle measured the total pressure in the combustion chamber for use in air-flow and combustor-efficiency calculations. Fuel flows to both the combustion-type preheater and the engine were measured by means of calibrated rotameters. The air flow to the preheater was measured with an A.S.M.E. type flat-plate orifice.

PROCEDURE

Simulated Flight Conditions

A Mach number of approximately 3.0 was obtained ahead of the engine by means of a convergent-divergent nozzle (ref. 3). The total temperature of the air entering the surge tank was raised to 1100° R by means of the combustion-type preheater to simulate the standard total temperature for a flight Mach number of 3.0 at altitudes above the tropopause. The total pressure in the surge tank was varied to provide a range of engine air flows from 10.27 to 5.60 pounds per second per square foot of combustion-chamber cross-sectional area, corresponding to simulated altitudes in the jet from 61,700 to 74,400 feet, respectively. The engine, however, by virtue of its inlet and exit geometry, operated supercritically for all fuel-air ratios. The combustion-chamber pressures are therefore somewhat lower for the simulated altitudes of this investigation than are obtainable with a better matching of the inlet and exit geometry. The performance of the two configurations investigated is therefore presented both in terms of engine air flow per square foot of combustion-chamber cross-sectional area (unit air flow) and in terms of corresponding simulated altitudes in the jet.

Method of Engine Operation

<u>Determination of pilot-burner performance</u>. - A 45-percent exhaust nozzle was installed on the engine to permit the determination of the

performance of the pilot burner alone at a combustion-chamber-inlet Mach number corresponding to combustor operation at an over-all fuel-air ratio of 0.02 with a 55-percent exhaust nozzle. Supersonic flow was established in the free-jet nozzle and then the throttling valve (fig. 1) was partly closed to raise the pressure level and reduce the velocities in the engine sufficiently to permit ignition of the pilot burner. When burning had been established, the throttling valve was opened and the engine exhaust nozzle was choked. The pilot-burner fuel flow was then varied to cover the range of fuel-air ratios from lean to rich blow-out. Several runs were made to determine the air flow through the pilot burner for burning and nonburning conditions. Under burning conditions, the air flow through the pilot burner was determined by means of an NACA mixture analyzer and fuel-flow measurements. Under nonburning conditions, the air flow through the pilot burner was determined with pilot-burner-discharge instrumentation for a range of combustion-chamber-inlet Mach numbers obtained by varying the position of the throttling valve downstream of the engine exhaust nozzle.

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Determination of complete combustor performance. - After the performance of the pilot burner alone had been established, the performance of the pilot burner and the main-stream combustor was determined with a 55-percent exhaust nozzle. The ignition procedure was the same as before except that in addition to the pilot burner, the inner zone was also ignited and a fuel-air ratio of about 0.02 established. While the engine over-all fuel-air ratio was held at 0.02, the fuel flow to the pilot was varied to determine the division of fuel flow between the pilot burner and inner-zone fuel systems giving peak combustor efficiency. The pilot fuel flow was then held constant at the optimum value as the fuel flow to the inner zone was varied to cover the range of fuel-air ratios up to the pumping capacity of the inner-zone fuel system. After the inner-zone performance had been determined, the inner-zone and pilot-burner fuel flows were held at their optimum value (peak combustor efficiency) by holding the pilot-burner and inner-zone fuel manifold pressures constant. The fuel flow to the outer zone was then initiated and varied to obtain engine performance at the high fuel-air ratios.

CALCULATIONS

The engine fuel-air ratio was calculated as the ratio of engine fuel flow to the unburned air flow entering the engine. The combustor efficiency was taken as the ratio of ideal to actual fuel-air ratio, where the ideal fuel-air ratio was that necessary to obtain, with an ideal combustion process, the total pressure measured at the exit of the engine combustion chamber for the air flow under consideration. The specific fuel consumption was calculated as the ratio of the engine fuel flow in pounds per hour to the net internal thrust.

The symbols used in this report are listed in appendix A. The methods used to calculate engine air flow, fuel-air ratio, combustor efficiency, combustion-chamber-inlet Mach number, pilot-burner air flow under nonburning and burning conditions, and specific fuel consumption are outlined in appendix B.

RESULTS AND DISCUSSION

Performance of High-Heat-Release Pilot Burner

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The pilot-burner combustor efficiency was determined for configuration 1 at combustor-inlet Mach numbers of about 0.2 and combustor-outlet total pressures of about 1500 pounds per square foot.

The pilot-burner combustor efficiency is presented in figure 7 as a function of both over-all engine fuel-air ratio (based on total engine air flow) and local fuel-air ratio in the pilot burner (based on pilot-burner air flow). Combustor efficiency, not combustion efficiency, is presented here and throughout the report; the details of the calculation are outlined in appendix B. A peak pilot-burner combustor efficiency of 0.93 occurred at an over-all fuel-air ratio of 0.0054. The pilot burner had an operable range of over-all fuel-air ratios from about 0.0037 to about 0.0081.

Figure 8 presents the fraction of engine air flow passing through the pilot burner as a function of combustion-chamber-inlet Mach number for burning and nonburning conditions. At a combustion-chamber-inlet Mach number of 0.055, the pilot-burner air-flow - engine air-flow ratio was 0.12 and increased gradually to 0.14 at a combustion-chamber inlet Mach number of 0.295. The agreement of the burning and nonburning measurements indicates that the amount of air passing through the pilot burner was not significantly altered by variations of combustion-chamber-inlet Mach number or by combustion in the main combustor and in the pilot burner.

The pilot-burner combustor efficiency and the pilot-burner capture air flow were considered satisfactory since the combination satisfied the design objective.

Performance of Combustion-Chamber Configurations

Configuration 1. - The variation of combustor efficiency with fuel-air ratio for configuration 1 with four different inner-zone fuel-injection systems is shown in figure 9. Data are shown for fuel injection in only the inner zone and for a unit air flow of 6.88. As can be

seen in figure 9, fuel-distribution system d had a peak efficiency of 0.84 at a fuel-air ratio of 0.02 and because it had the highest combustor efficiency at a fuel-air ratio of 0.02, the region of primary interest, it was retained for subsequent runs.

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The performance of configuration 1 is presented in figure 10 for unit air flows of 5.63, 6.94, and 10.27. Combustor efficiency is plotted against fuel-air ratio in figure 10(a). The minimum fuel-air ratio operating point for each air flow was obtained with the pilot burner operating alone. The inner zone was operated from a fuel-air ratio of about 0.006 to the pumping limit of the inner-zone fuel system. As the inner-zone fuel flow increased, the combustor efficiency first decreased and then increased until maximum values were reached at a fuel-air ratio of about 0.02. Further increases in inner-zone fuel flow resulted in moderate decreases in efficiency for all three air flows. At a fuel-air ratio of 0.02, combustor efficiency increased from 0.80 to 0.86 as the unit air flow was increased from 5.63 to 10.27.

The change in the combustor efficiency for initial increments of outer-zone fuel flow was similar to that obtained for initial increments of inner-zone fuel flow and is typified by the dotted portion of the curve shown in figure 10(a) for a unit air flow of 5.63. For other air flows, the corresponding dotted portions of the curves are omitted for clarity. The peak combustor efficiency with both zones operating was about 0.89 for the three unit air flows investigated and occurred at a fuel-air ratio of about 0.06.

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The burner total-pressure ratio for configuration 1 is presented in figure 10(b) for various fuel-air ratios. At a fuel-air ratio of 0.02, the total-pressure ratio is about 0.87.

Environmental conditions associated with the combustor are shown in figures 10(c) and 10(d), where the variation, respectively, of combustion-chamber-outlet total pressure and combustion-chamber-inlet Mach number with fuel-air ratio are given. As previously noted in figure 10(a), the combustor efficiency increased from 0.80 to 0.86 at a fuel-air ratio of 0.02 as the unit air flow was increased. This increase in combustor efficiency was presumably caused by the increase in combustor pressure from about 900 to 1700 pounds per square foot absolute as can be seen in figure 10(c).

Configuration 2. - Reference 5 indicated that good performance characteristics were obtained at atmospheric pressure in a ram-jet combustor with a flame holder utilizing sloping-channel gutters. This good performance was believed to be primarily due to fuel-air mixing control in the combustion zone in addition to prereaction zone control employed in the design. Combustion was initiated in the wake of the upstream set of baffles and was substantially completed in the shielded

region downstream of the baffles. At lean fuel-air ratios, combustion occurred only in the primary zone and dilution with secondary air took place downstream of the shielded region. The use of a sloping baffle and conical shielded zone provided an expanding volume for the primary combustion region; a low flow velocity was thereby maintained which permitted combustion to be completed in a relatively short length. The performance of a similar flame holder investigated with the high-heat-release pilot burner is presented in figure 11 for unit air flows of 5.60 and 6.95.

At a fuel-air ratio of 0.02 the combustor efficiency of configura- 3035
tion 2 (fig. 11(a)) was from 5 to 8 percentage points higher than that obtained with configuration 1. As the inner-zone fuel-air ratio decreased from the point of maximum efficiency, a very rapid decrease in efficiency occurred for both unit air flows as contrasted with the relatively high combustor efficiency obtained with configuration 1 at fuel-air ratios below 0.02. No completely satisfactory explanation has been found for the difference in efficiency.

As the inner-zone fuel-air ratio increased beyond the point of maximum efficiency, the combustor efficiency decreased moderately for both unit air flows. For operation with both zones, the peak combustor efficiency of 0.91, which occurred at a fuel-air ratio of 0.046 (leaner than for configuration 1), was slightly higher than that for configuration 1.

At a fuel-air ratio of 0.02, the burner total-pressure ratio is 2 to 3 percentage points higher for configuration 2 than for configuration 1 (fig. 11(b)). Environmental conditions associated with the combustor are shown in figures 11(c) and 11(d), where the variation, respectively, of combustion-chamber-outlet total pressure and combustion-chamber-inlet Mach number with fuel-air ratio are given.

Operating characteristics. - The combustor stability of configurations 1 and 2 was dependent upon pilot-burner fuel flow; that is, the combustors operated stably and smoothly when the pilot burner operated at a fuel flow which gave the highest combustion efficiency at an overall fuel-air ratio of 0.02. When small deviations from this fuel flow were made, the combustors operated roughly with premature blow-outs. The combustors would not operate without fuel flow to the pilot burner.

When configuration 2 had operated for 13 minutes at an air flow which gave about atmospheric pressure in the combustor, a pilot burner failure occurred as shown in figure 12. Similar failures might occur with this combustor when the flight plan required burning at low altitudes, as would be the case if the ram-jet engine furnished thrust for acceleration and climb.

Comparison of configurations on basis of specific fuel consumption. - The range of a ram-jet engine is influenced by both the burner total-pressure ratio and the combustor efficiency. In order to compare the cruise performance of the two configurations by means of a single parameter which includes the effects of both factors, figure 13 is presented where specific fuel consumption is plotted against net internal thrust per pound of air flow. Two typical configurations, having small pilots and the same diffuser as configurations 1 and 2, reported in reference 1 are also presented in this comparison as representative of current ram-jet combustors. The combustion-chamber lengths and over-all engine lengths of each configuration are given in figure 13. Curves of constant fuel-air ratio are also shown for reference. The minimum specific fuel consumption for each configuration occurred at a fuel-air ratio of about 0.02. Configuration 2 had the lowest specific fuel consumption with 2.19. This was 6 percent lower than for configuration 1 and 13 percent lower than for configuration A; it is therefore seen that for these configurations having approximately the same combustion-chamber length, the best specific fuel consumption was obtained with the sloping radial-gutter flame holder and the high-heat-release pilot burner. Configuration B had a small pilot burner but the same over-all engine length as those configurations employing the high-heat-release pilot burner (configurations 1 and 2). Configuration B had a combustion-chamber length that was longer by the difference in length of the large pilot burners and had a specific fuel consumption of 2.21. Thus, it appears that the increased length required to accommodate the high-heat-release pilot burner of configuration 2 had an equivalent effect when utilized as part of the combustion chamber in configuration B. In view of this, it is doubtful that the complication introduced by the high-heat-release pilot burner can be justified. However, with additional development, it may be possible to rearrange the high-heat-release pilot burner configurations so that even better performance can be realized; the additional complication may then be justified.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the performance of two 20-inch ram-jet engine combustors utilizing a high-heat-release pilot burner which captured about 12 percent of the combustor air flow. A configuration employing a flame holder composed of two annular V-gutters and three large radial gutters had a peak combustor efficiency of 0.84 at a fuel-air ratio of 0.02 and approximately 1100 pounds per square foot combustor pressure.

At identical combustor conditions, a configuration employing a flame holder composed of sloping radial gutters emanating from the pilot burner had a peak combustor efficiency of 0.89. The high-heat-release

pilot burner configuration with a sloping radial-gutter flame holder had about the same minimum specific fuel consumption (2.2) as a typical small pilot burner configuration having an annular V-gutter flame holder and the same over-all engine length. Thus, for these particular configurations, it is doubtful that the additional complication introduced by the high-heat-release pilot burner can be justified.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 18, 1953

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APPENDIX A

SYMBOLS

The following symbols are used in this report:

A	area, sq ft
a	local speed of sound, ft/sec
B	fraction of supersonic jet flow entering engine inlet
C_d	discharge coefficient of exhaust nozzle
C_V	nozzle velocity coefficient
$F_{n,i}$	net internal thrust, lb
f/a	engine fuel-air ratio
$(f/a)'$	ideal fuel-air ratio
$(f/a)_p$	fuel-air ratio of preheater
$(f/a)_s$	stoichiometric fuel-air ratio
g	acceleration due to gravity, 32.2 ft/sec^2
M	Mach number
P	total pressure, lb/sq ft abs
p	static pressure, lb/sq ft abs
R	gas constant, (ft)(lb)/(lb)($^{\circ}$R)
T	total temperature, $^{\circ}$R
t	static temperature, $^{\circ}$R
sfc	specific fuel consumption, $\frac{\text{lb of fuel}}{\text{(hr)(lb net internal thrust)}}$
V	velocity, ft/sec
W	engine-inlet air flow, (containing preheater products of combustion), lb/sec

W_a air flow to preheater, lb/sec

$W_{f,e}$ fuel flow to engine (including pilot fuel flow), lb/sec

$W_{f,P}$ fuel flow to pilot, lb/sec

$W_{f,p}$ fuel flow to preheater, lb/sec

W_P air flow through pilot burner, lb/sec

W_u unburned air flow entering engine, lb/sec

W/A_4 engine unit air flow, lb/sec per sq ft combustion chamber cross sectional area

γ ratio of specific heats

η combustor efficiency

ρ density, lb/cu ft

Subscripts:

0 free stream

2 subsonic-diffuser exit

2' conditions at station 2 adjusted to combustion-chamber area

2" pilot-burner discharge

4 exhaust-nozzle inlet

5 exhaust-nozzle minimum area

6 station downstream of exhaust-nozzle exit

c cold (i.e., engine not burning)

h hot (i.e., engine burning)

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APPENDIX B

METHODS OF CALCULATION

Engine inlet-air flow. - The engine exhaust nozzle served as a convenient metering orifice for determining the rate of flow of air through the engine for nonburning conditions. Inasmuch as the diffuser was operating supercritically at all times, the inlet air flow, at a given inlet total pressure, was the same for burning and nonburning conditions. The engine air flow was calculated from the mass flow equation

$$W = \rho_{5,c} C_{d,c} A_5 V_{5,c} \tag{1}$$

This was expressed as

$$W = \frac{P_{5,c} C_{d,c} A_5 \sqrt{\gamma g}}{\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \sqrt{RT_{5,c}}} \tag{2}$$

where $P_{5,c}$ and $T_{5,c}$ were assumed equal to $P_{4,c}$ and T_0, respectively. The exhaust nozzle was choked. The exhaust-nozzle discharge coefficient $C_{d,c}$ was assumed to be 0.985. Leakage through the engine flanges was assumed to be negligible.

Engine fuel-air ratio. - The engine fuel-air ratio was defined as the ratio of the engine fuel flow to the unburned air passing through the engine inlet. Leaving the preheater was a gas which had a fuel-air ratio of

$$(f/a)_p = \frac{W_{f,p}}{W_a} \tag{3}$$

where W_a is the preheater air flow measured by the A.S.M.E. flat-plate orifice. It was found that the preheater combustion efficiency was nearly 100 percent. The ratio B of the engine-inlet air flow to the supersonic nozzle flow was constant for all inlet pressures. The unburned air entering the engine was then

$$W_u = B\, W_a \left[1 - \frac{(f/a)_p}{(f/a)_s}\right] \tag{4}$$

This is different from W, which includes preheater products of combustion. The engine fuel-air ratio was then

$$f/a = \frac{W_{f,e}}{B\ W_a\left[1 - \frac{(f/a)_p}{(f/a)_s}\right]} \tag{5}$$

Because it was more convenient to measure the engine-inlet air flow W than $B\ W_a$, use was made of the following relation:

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$$W = B(W_a + W_{f,p}) = B\ W_a\left[1 + (f/a)_p\right] \tag{6}$$

Rearranging gives

$$B\ W_a = \frac{W}{\left[1 + (f/a)_p\right]} \tag{7}$$

Substitution of equation (7) in equation (5) gives

$$f/a = \frac{W_{f,e}}{W}\left[\frac{1 + (f/a)_p}{1 - \frac{(f/a)_p}{(f/a)_s}}\right] \tag{8}$$

<u>Combustor efficiency</u>. - The combustor efficiency η was defined as

$$\eta = \frac{(f/a)'}{f/a} \tag{9}$$

where f/a is given by equation (8) and $(f/a)'$ is the ideal fuel-air ratio which would have produced the same burner pressure P_4 as was measured for the burning conditions under consideration. Thus, the efficiency was related only to burner pressure, obviating the direct measurement of the high combustion-chamber temperatures.

The determination of $(f/a)'$ was implemented in the following way. Because the engine-inlet diffuser operated supercritically at all times, the entering air flow at a given altitude was the same for the nonburning and burning conditions and could be expressed as

$$W = \rho_{5,c}C_{d,c}A_5V_{5,c} = \frac{\rho_{5,h}C_{d,h}A_5V_{5,h}}{1 + \frac{W_{f,e}}{W}} \tag{10}$$

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By use of the equation of state, converting static pressure and temperature to total values and velocity to Mach number, and rearranging equation (10), the following expressions may be written

$$P_{5,h} = \frac{W\left(1 + \frac{W_{f,e}}{W}\right)}{C_{d,h}A_5M_{5,h}} \sqrt{\frac{R_hT_{5,h}}{\gamma_h g}} \left(1 + \frac{\gamma_h - 1}{2} M_{5,h}^2\right)^{\frac{\gamma_h+1}{2(\gamma_h-1)}} \tag{11}$$

and

$$P_{5,c} = \frac{W}{C_{d,c}A_5M_{5,c}} \sqrt{\frac{R_cT_{5,c}}{\gamma_c g}} \left(1 + \frac{\gamma_c - 1}{2} M_{5,c}^2\right)^{\frac{\gamma_c+1}{2(\gamma_c-1)}} \tag{12}$$

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By dividing equation (11) by equation (12), assuming that

$$P_{5,c} = P_{4,c} \tag{13}$$

$$P_{5,h} = P_{4,h} \tag{14}$$

$$T_{5,c} = T_{4,c} = T_0 \tag{15}$$

$$T_{5,h} = T_{4,h} \tag{16}$$

$$C_{d,h} = C_{d,c} \tag{17}$$

and noting that

$$M_{5,c} = M_{5,h} = 1 \tag{18}$$

the following equation is obtained:

$$\frac{P_{4,h}}{P_{4,c}} = \sqrt{\frac{T_{4,h}}{T_0}}\left(1 + \frac{W_{f,e}}{W}\right)\sqrt{\frac{\left[\left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}\left(\frac{R}{\gamma}\right)\right]_h}{\left[\left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}\left(\frac{R}{\gamma}\right)\right]_c}} \tag{19}$$

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The pressure ratio $P_{4,h}/P_{4,c}$ was then evaluated for various ideal fuel-air ratios by using theoretical combustion charts, which included the effects of dissociation, to find $T_{4,h}$. These data were then plotted as $(f/a)'$ against $P_{4,h}/P_{4,c}$. By referring to this plot, the theoretical fuel-air ratio $(f/a)'$ could be obtained for each value of $P_{4,h}/P_{4,c}$ measured in the engine combustion chamber.

The combustor efficiency as defined herein is not a chemical combustion efficiency such as a heat-balance or enthalpy-rise method would indicate. The combustor efficiency based on total-pressure measurement is, however, more representative of over-all engine performance, in view of the fact that it indicates how effectively the fuel is being used to provide thrust potential rather than how completely the fuel is being burned.

Combustion-chamber-inlet Mach number. - The combustion-chamber-inlet Mach number was calculated by using the engine-inlet air flow W, the static pressure measured in the engine inlet diffuser p_2, the ambient total temperature T_0, and the maximum area of the combustion chamber (314.2 sq in.).

Pilot-burner air flow. - The air flow through the pilot burner for nonburning conditions was calculated from the mass-flow equation. (The pilot-burner discharge coefficient was assumed to be 1.0.)

$$W_{2''} = \rho_{2''}A_{2''}V_{2''} \tag{20}$$

This was expressed as

$$W_{2''} = \frac{p_{2''}A_{2''}}{\sqrt{RT_{2'',c}}}\sqrt{\frac{2\gamma g}{\gamma-1}\left(\frac{P_{2''}}{p_{2''}}\right)^{\frac{\gamma-1}{\gamma}}\left[\left(\frac{P_{2''}}{p_{2''}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{21}$$

where $T_{2''}$ was assumed equal to T_0.

The air flow through the pilot burner for burning conditions was determined as follows: A fuel-air ratio survey was made by means of an NACA Mixture Analyzer (ref. 4) at the pilot-burner discharge. The pilot-burner fuel flow was measured by a calibrated rotameter, so the pilot-burner air flow was found as

$$W_{2''} = \frac{W_{f,p}}{(f/a)_{2''}} \tag{22}$$

Specific fuel consumption. - The specific fuel consumption was calculated as the ratio of the engine fuel flow in pounds per hour to the net internal thrust. Thus

$$sfc = \frac{(W_{f,e})(3600)}{F_{n,i}} \tag{23}$$

where $F_{n,i}$, the net internal thrust, is given by

$$F_{n,i} = \frac{W}{g}V_6C_V(1 + f/a) + A_6(p_6 - p_0) - \frac{W}{g}V_0 \tag{24}$$

By substituting equation (24) into equation (23) and rearranging, equation (23) can be expressed as

$$sfc = \frac{\left(\frac{W_{f,e}}{W}\right)(g)(3600)}{V_6C_V(1 + f/a) + \frac{A_6}{W}g(p_6 - p_0) - V_0} \tag{25}$$

For this calculation $W_{f,e}/W$ was considered equivalent to f/a of equation (8). The exhaust gases were assumed to be completely expanded to atmospheric pressure. Therefore, the quantity $\frac{A_6}{W}g(p_6 - p_0)$ is zero. C_V was taken as 0.95.

The velocity V_6 was determined as follows:

$$V_6 = M_6 a_6 \tag{26}$$

$$= M_6\sqrt{\gamma_6 g R_6 t_6} \tag{27}$$

$$= M_6\sqrt{\frac{(\gamma_6 g R_6 T_6)}{\left(1 + \frac{\gamma_6 - 1}{2} M_6^{\,2}\right)}} \tag{28}$$

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M_6 was found as the Mach number resulting from ideal expansion through the pressure ratio P_4/p_0, where P_4/p_0 was determined as follows:

$$\frac{P_4}{p_0} = \frac{P_2}{P_0}\,\frac{P_4}{P_2}\,\frac{P_0}{p_0} \tag{29}$$

where P_2/P_0 was assumed to be 0.60 (readily obtained in practice) for all the data. The ratio P_4/P_2 was determined by the experimental curves of burner total-pressure ratio versus fuel-air ratio. The ratio P_0/p_0 was 36.7 (a constant corresponding to flight at a Mach number of 3.0).

The temperature T_6 was determined from T_0, the combustor efficiency, and a curve of temperature rise versus theoretical fuel-air ratio. Thus, all the quantities in equation (28) are determined.

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2. Calcote, H. F., Fenn, J. B., and Mullen, J. W., II: Correlation of Classical Combustion Quantities with Ram-Jet Burner Performance. Bumblebee Rep. No. 130, Experiment Inc., May 1950. (Contract NOrd 9756, Bur. Ord., U. S. Navy.)

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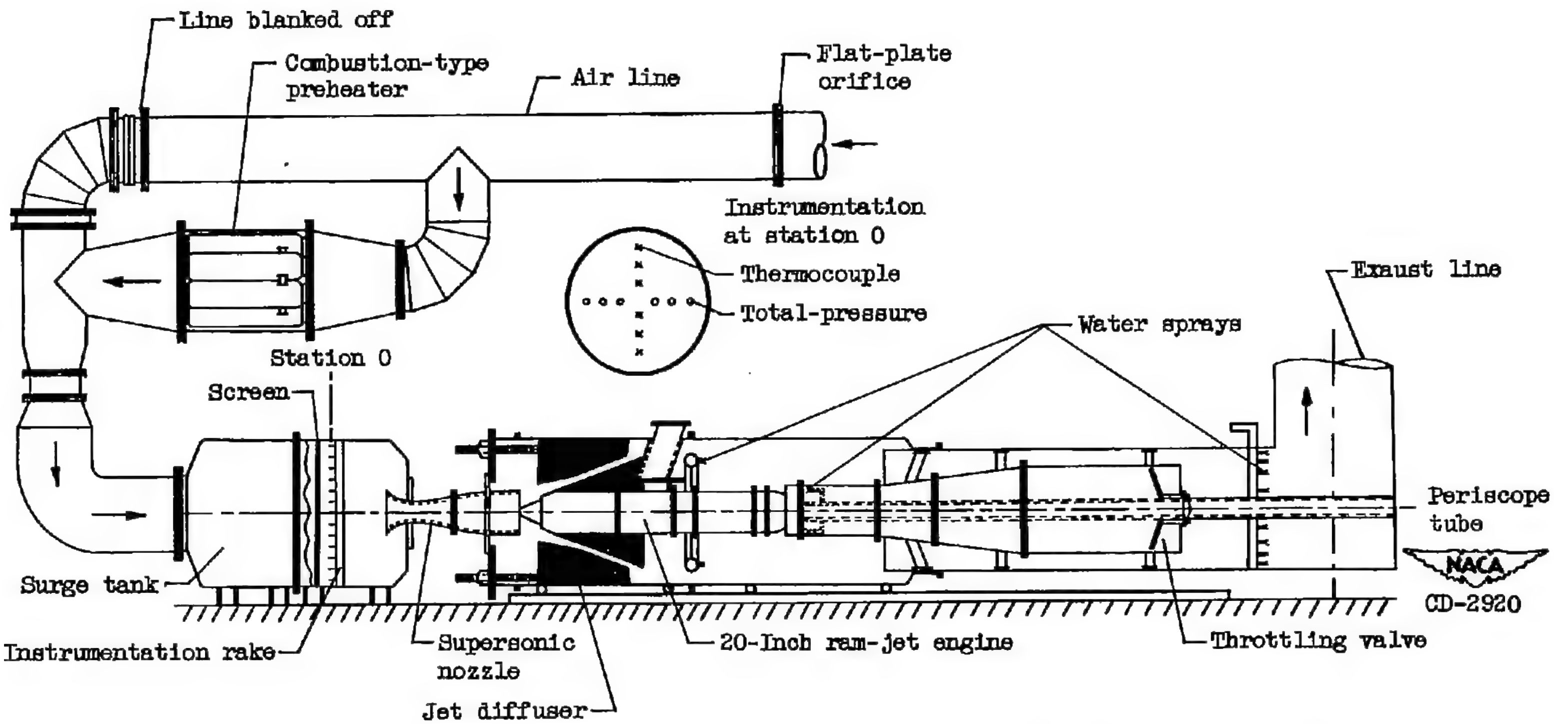


Figure 1. - Schematic diagram of free-jet facility with the 20-inch-diameter ram-jet engine installed.

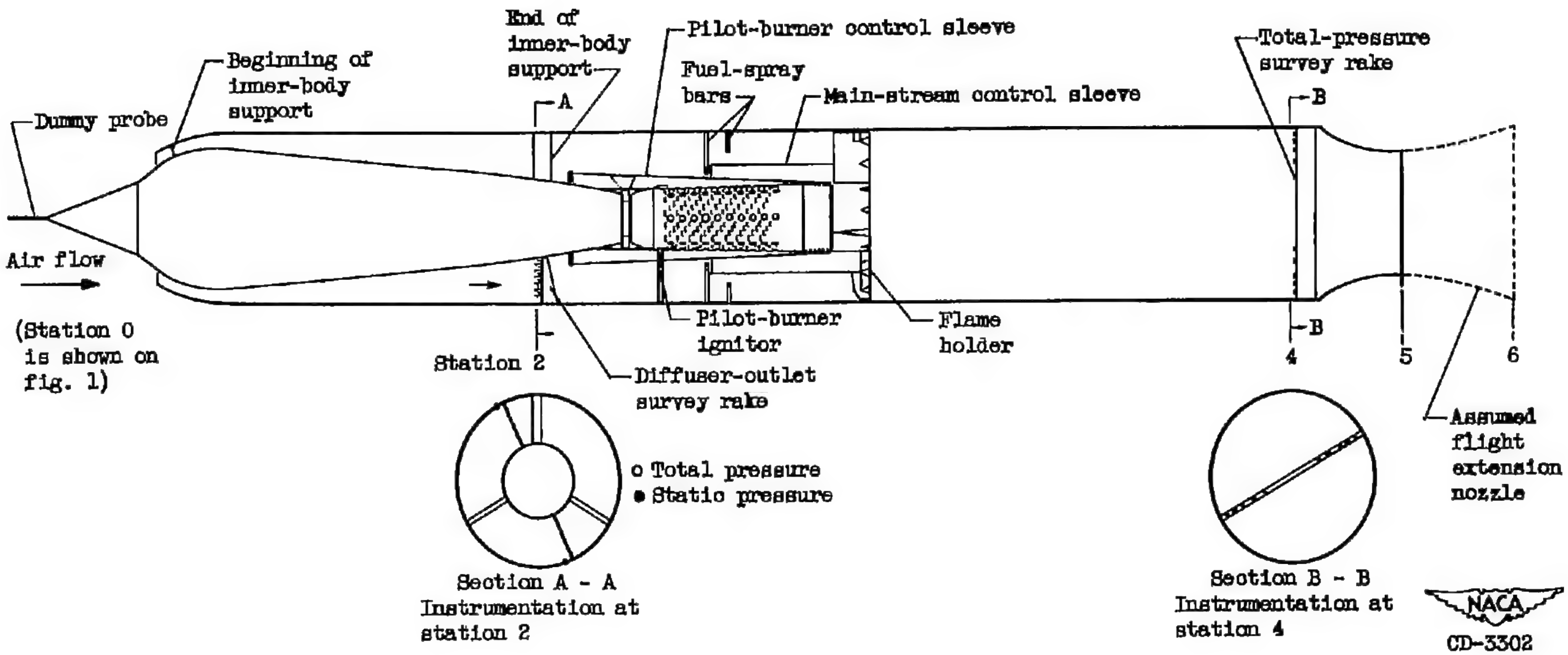


Figure 2. - Cross section of 20-inch-diameter ram-jet engine with configuration 1 installed.

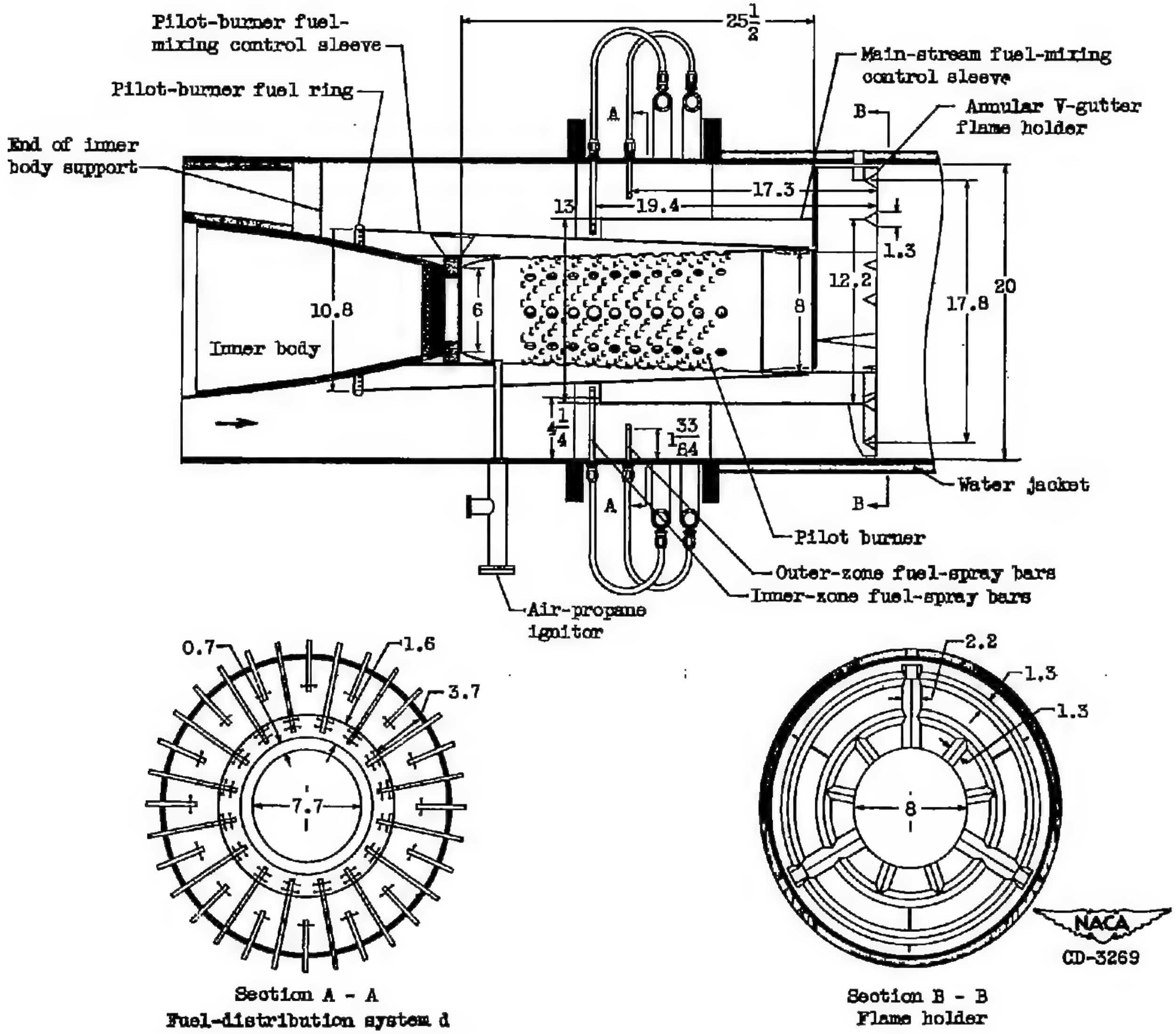


Figure 3. - Combustor configuration 1 with fuel-distribution system d. (All dimensions are in inches.)

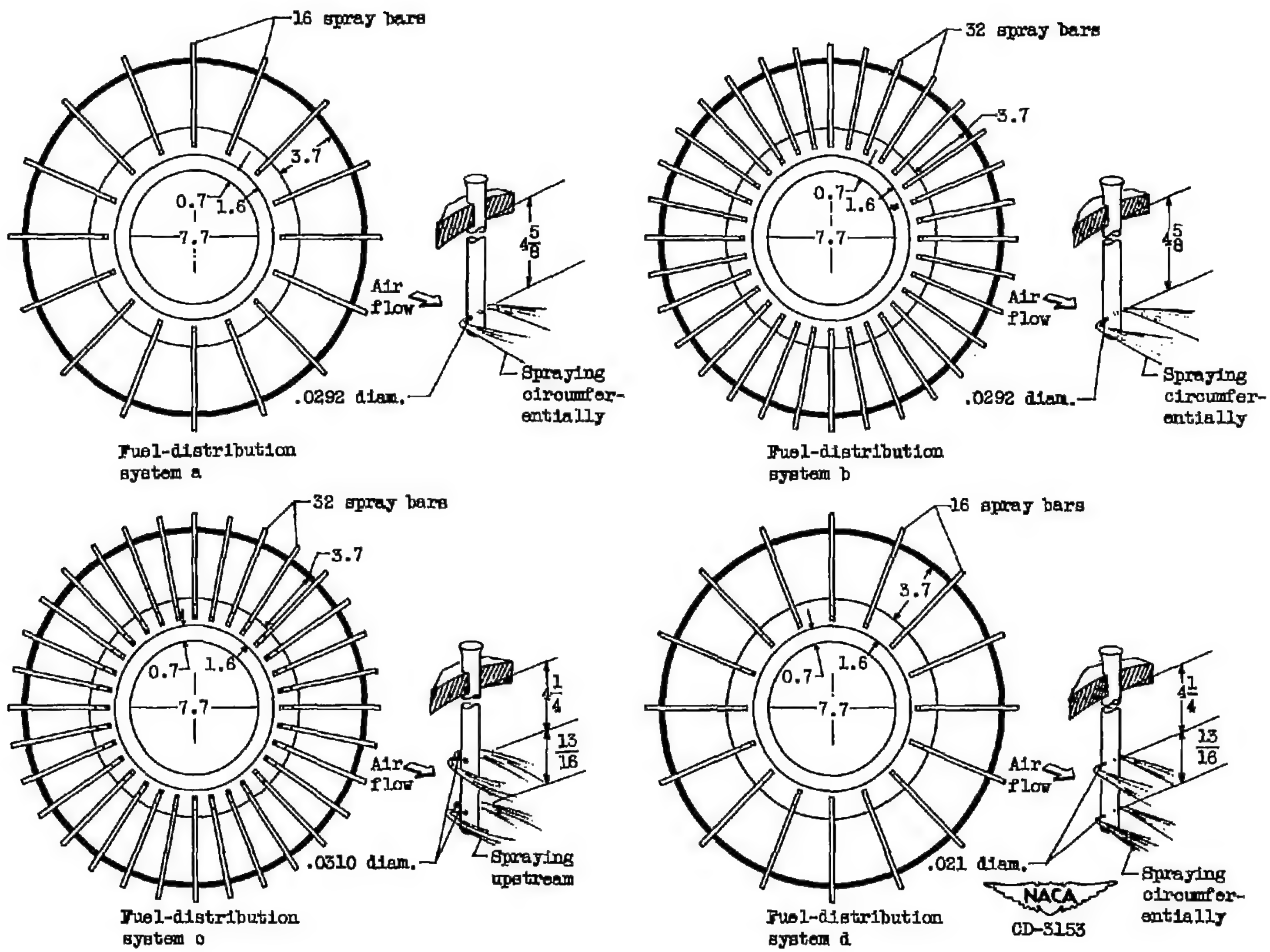
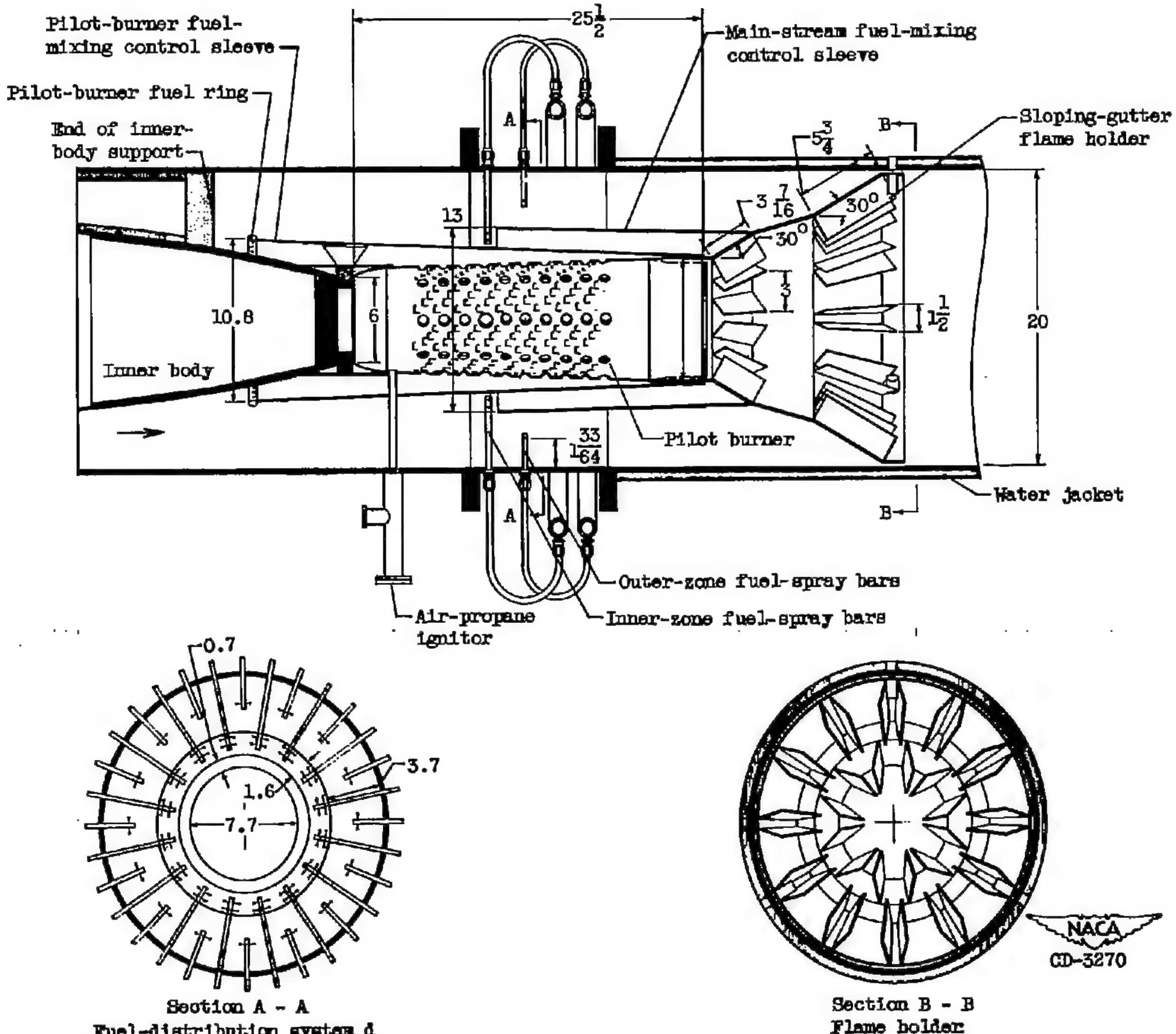


Figure 4. - Variations in inner-zone fuel-distribution system for configuration 1. (All dimensions are in inches.)



Section A - A
Fuel-distribution system d

Section B - B
Flame holder

Figure 5. - Combustor configuration 2 with fuel-distribution system d. (All dimensions are in inches.)

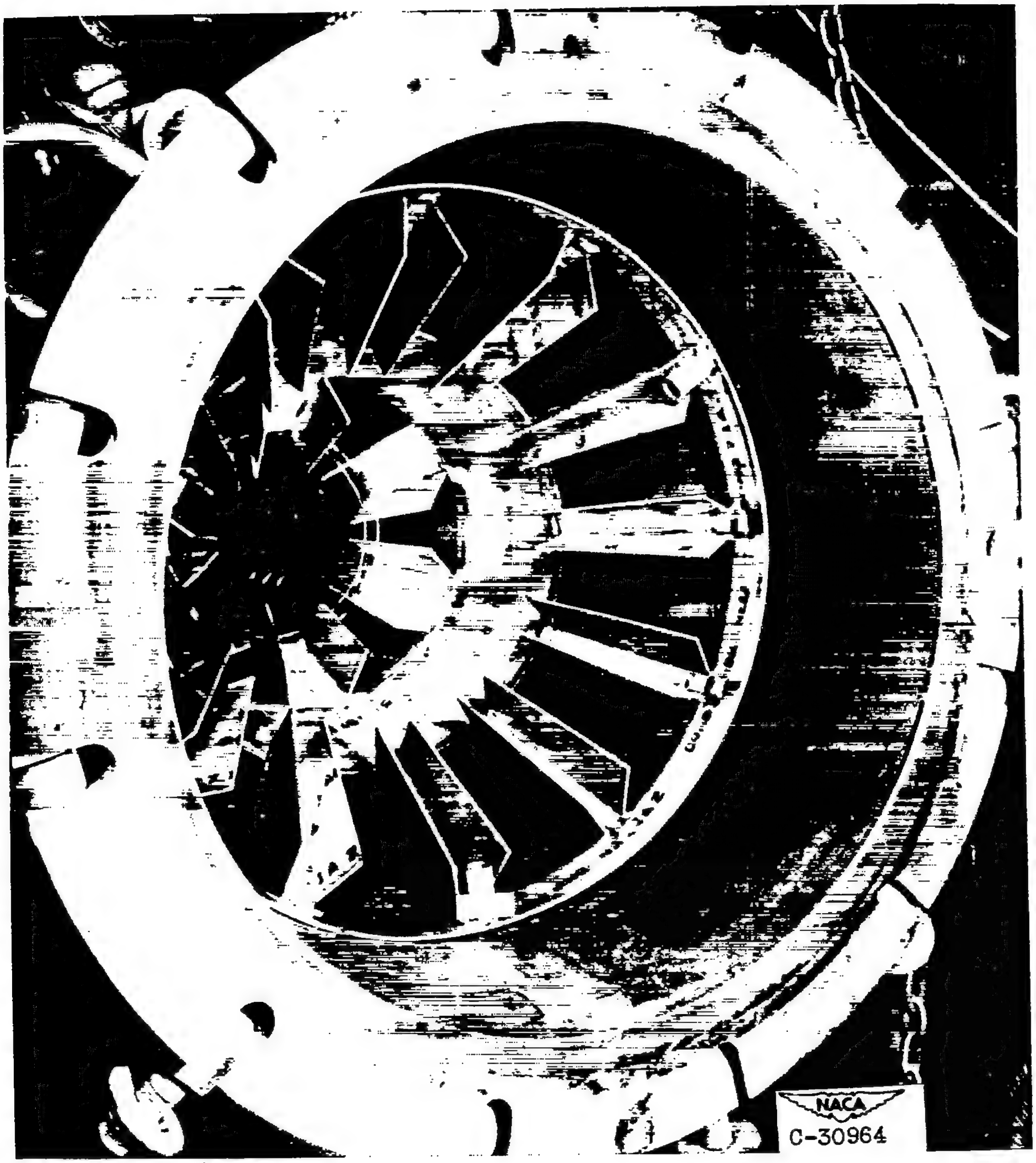


Figure 6. - Photograph of configuration 2 flame holder and pilot burner before operation.

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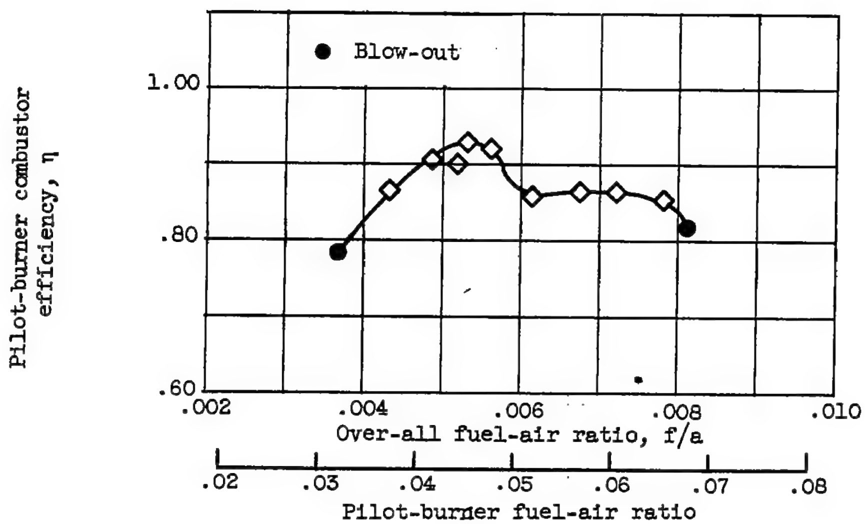

Figure 7. - Pilot-burner combustor efficiency. Configuration 1; combustion-chamber-exit total pressure, approximately 1500 pounds per square foot absolute; engine unit air flow, W/A_4, 6.79; corresponding altitude, 70,600 feet.

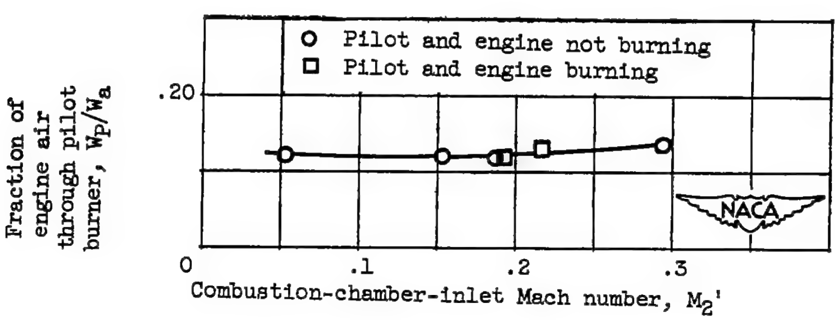

Figure 8. - Fraction of air passing through pilot burner for various combustion-chamber-inlet Mach numbers. Configuration 1; engine unit air flow, W/A_4, 6.88; corresponding altitude, 70,300 feet.

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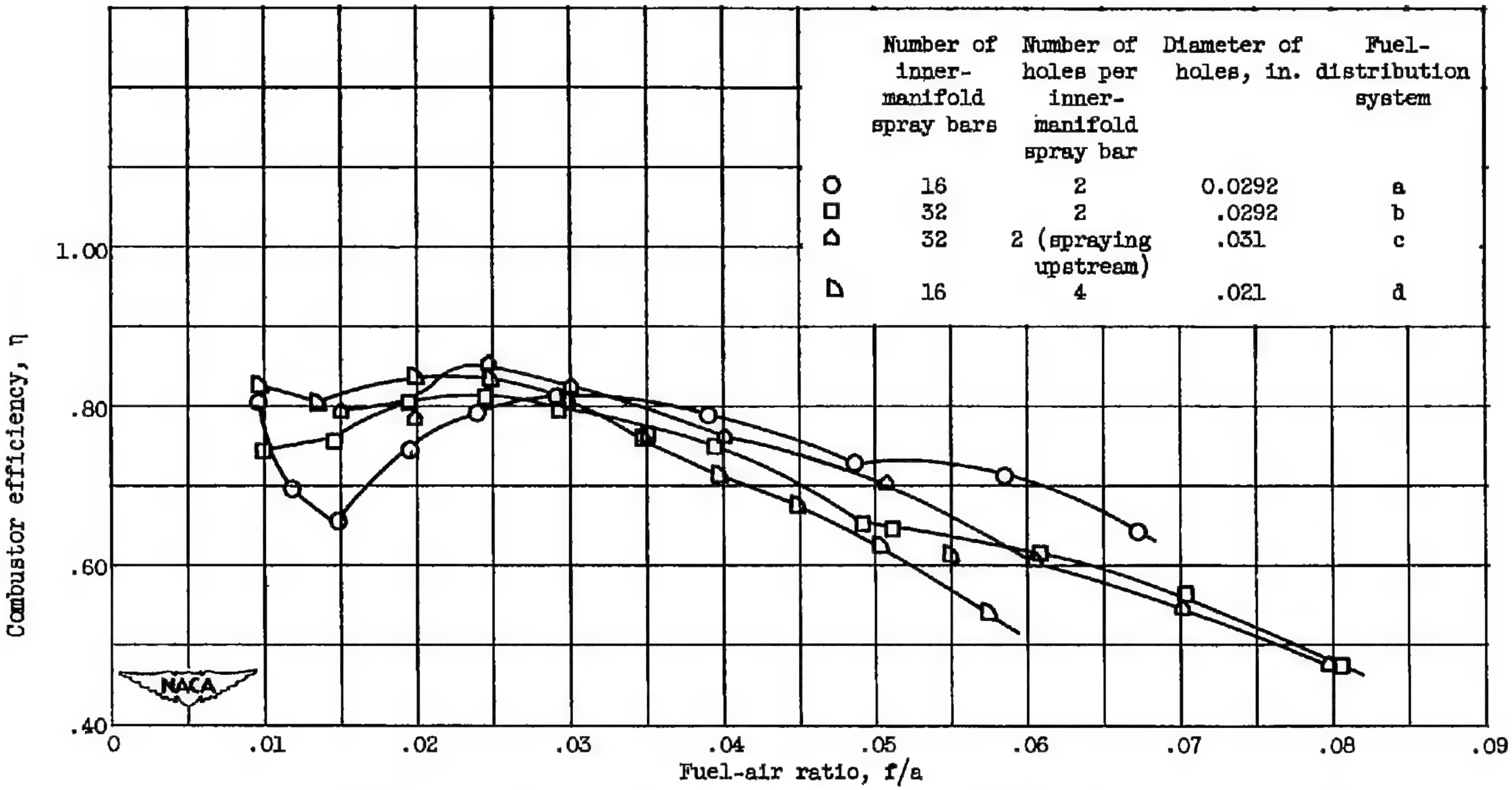

Figure 9. - Inner-zone combustor efficiency of configuration 1 with four different inner-zone fuel-injection systems. Engine unit air flow, W/A_4, 6.88; corresponding altitude, 70,300 feet.

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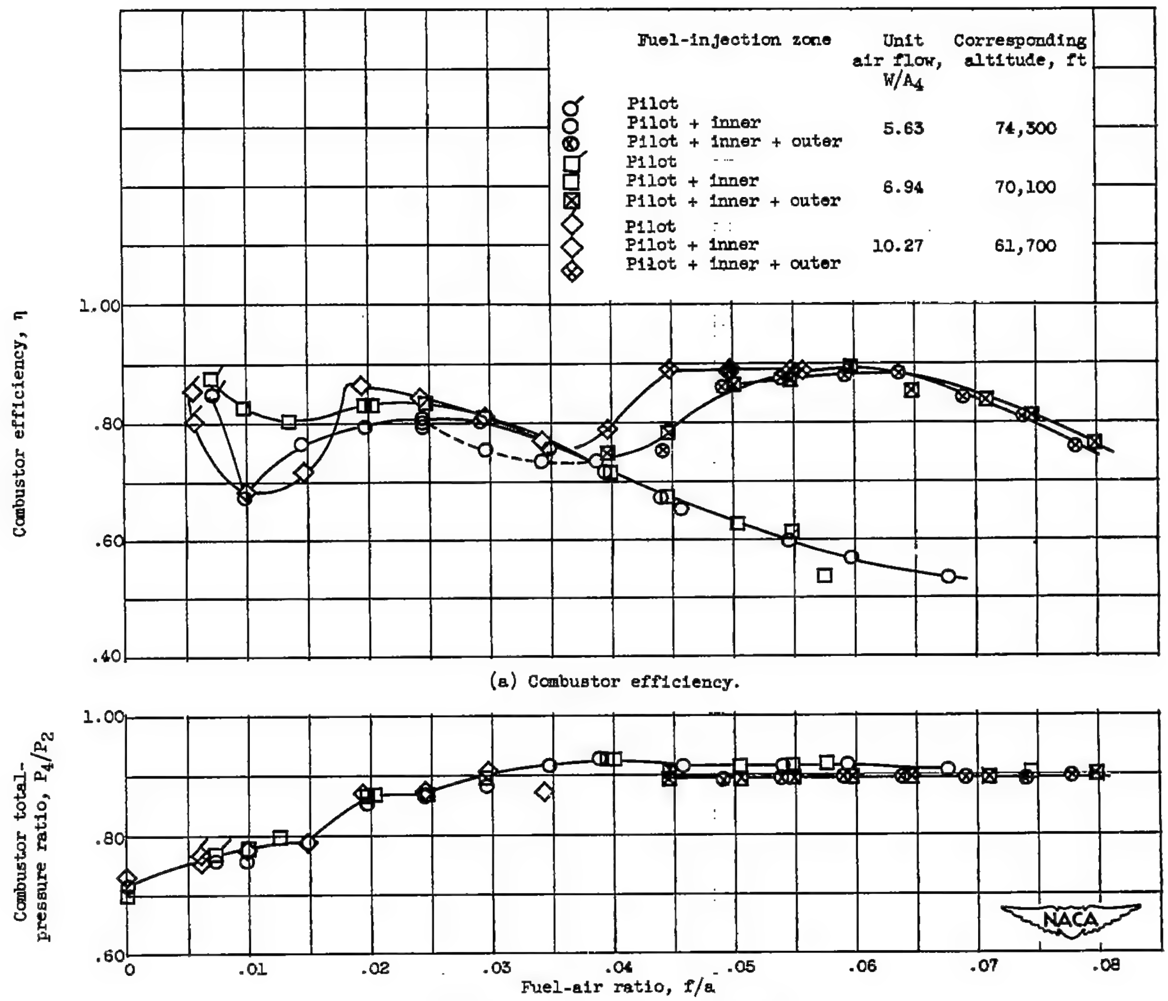

(a) Combustor efficiency.

(b) Combustor total-pressure ratio.

Figure 10. - Performance of configuration 1. Inner-zone fuel-injection system d.

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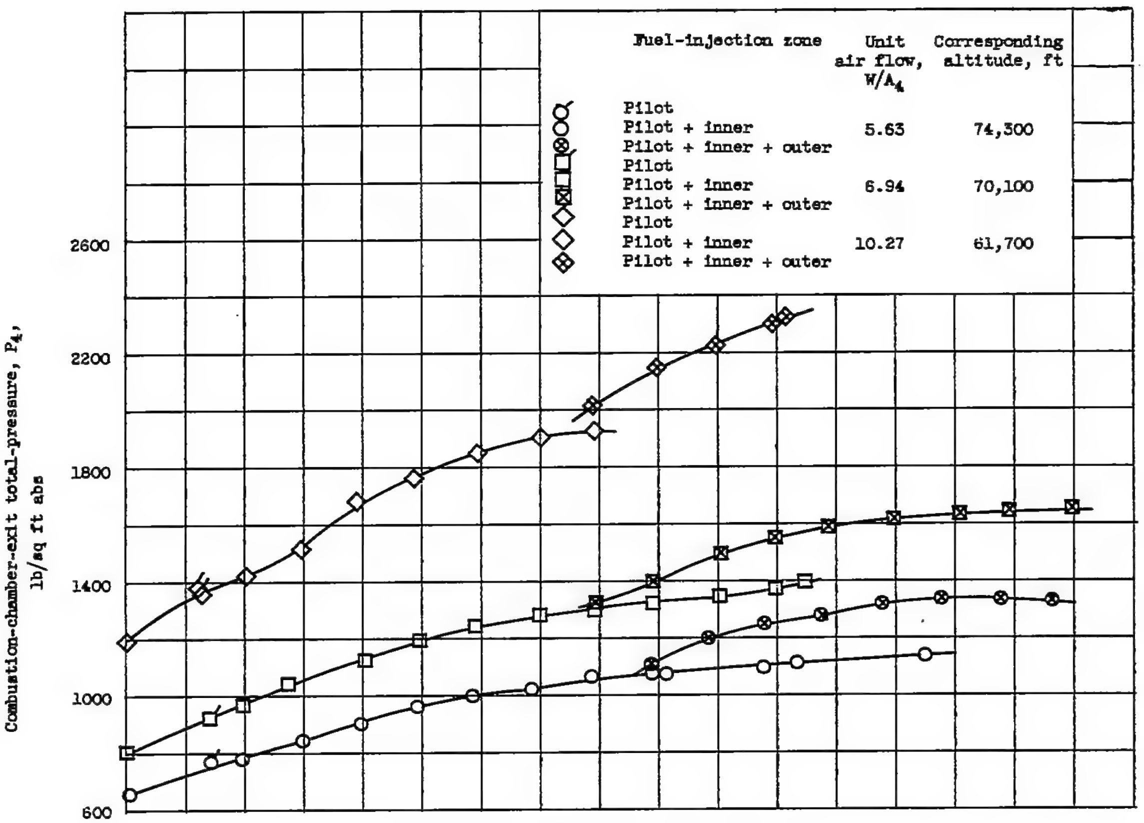
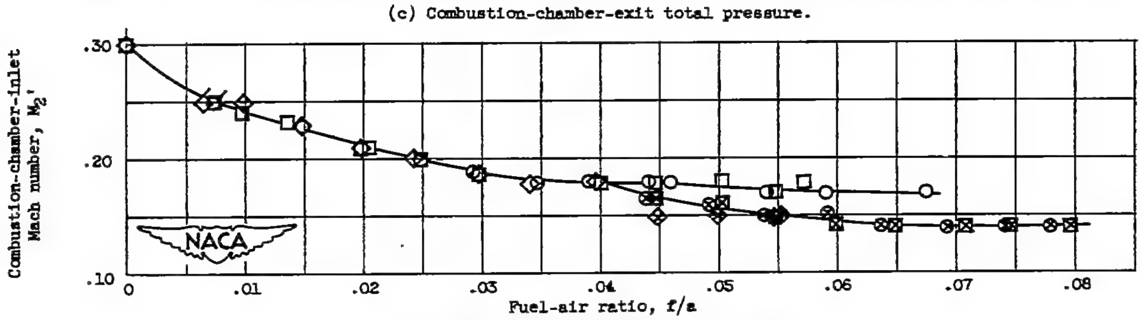


(c) Combustion-chamber-exit total pressure.



(d) Combustion-chamber-inlet Mach number.

Figure 10. - Concluded. Performance of configuration 1. Inner-zone fuel-injection system d.

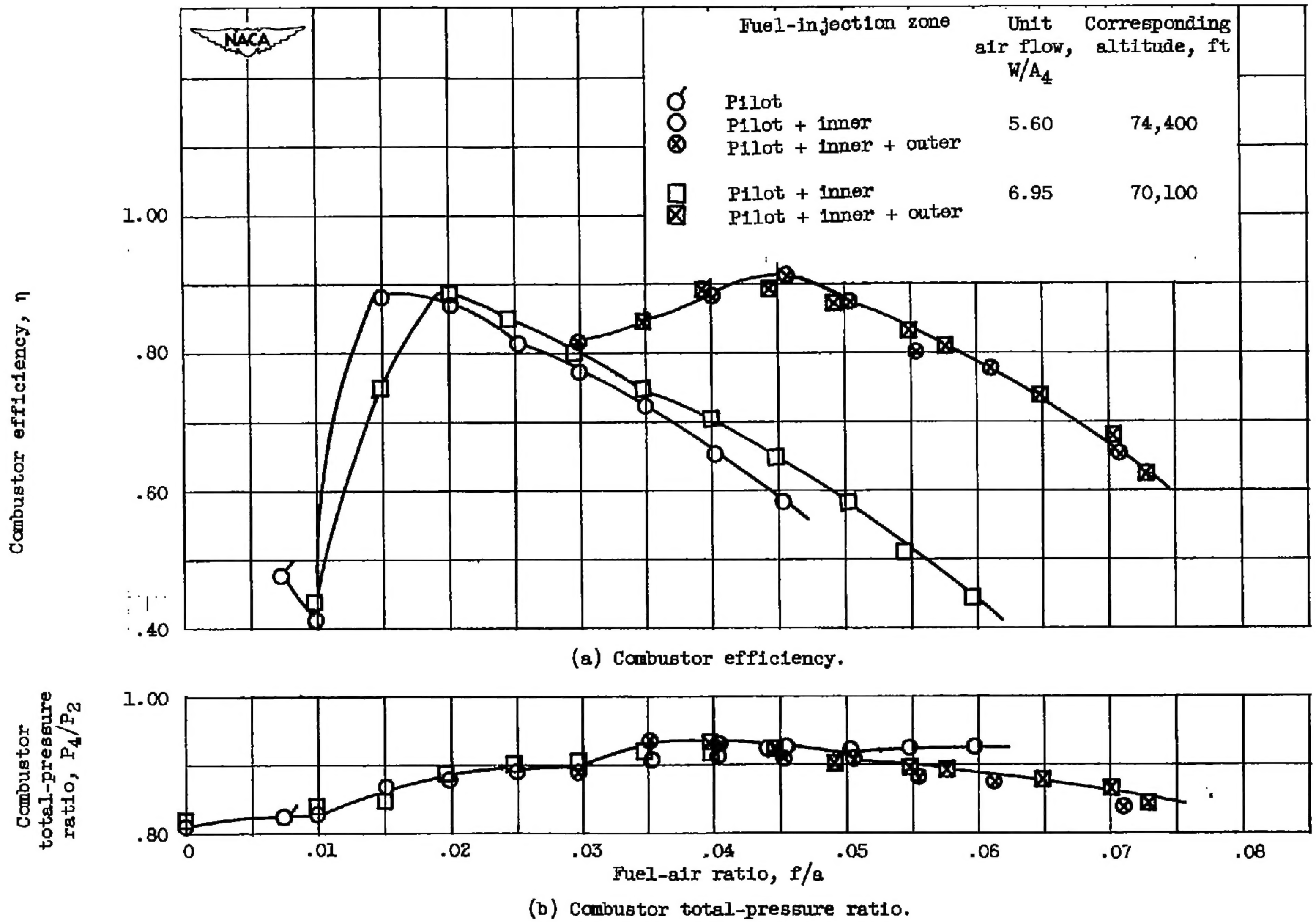


Figure 11. - Performance of configuration 2. High-heat-release pilot burner with sloping-gutter flame holder.

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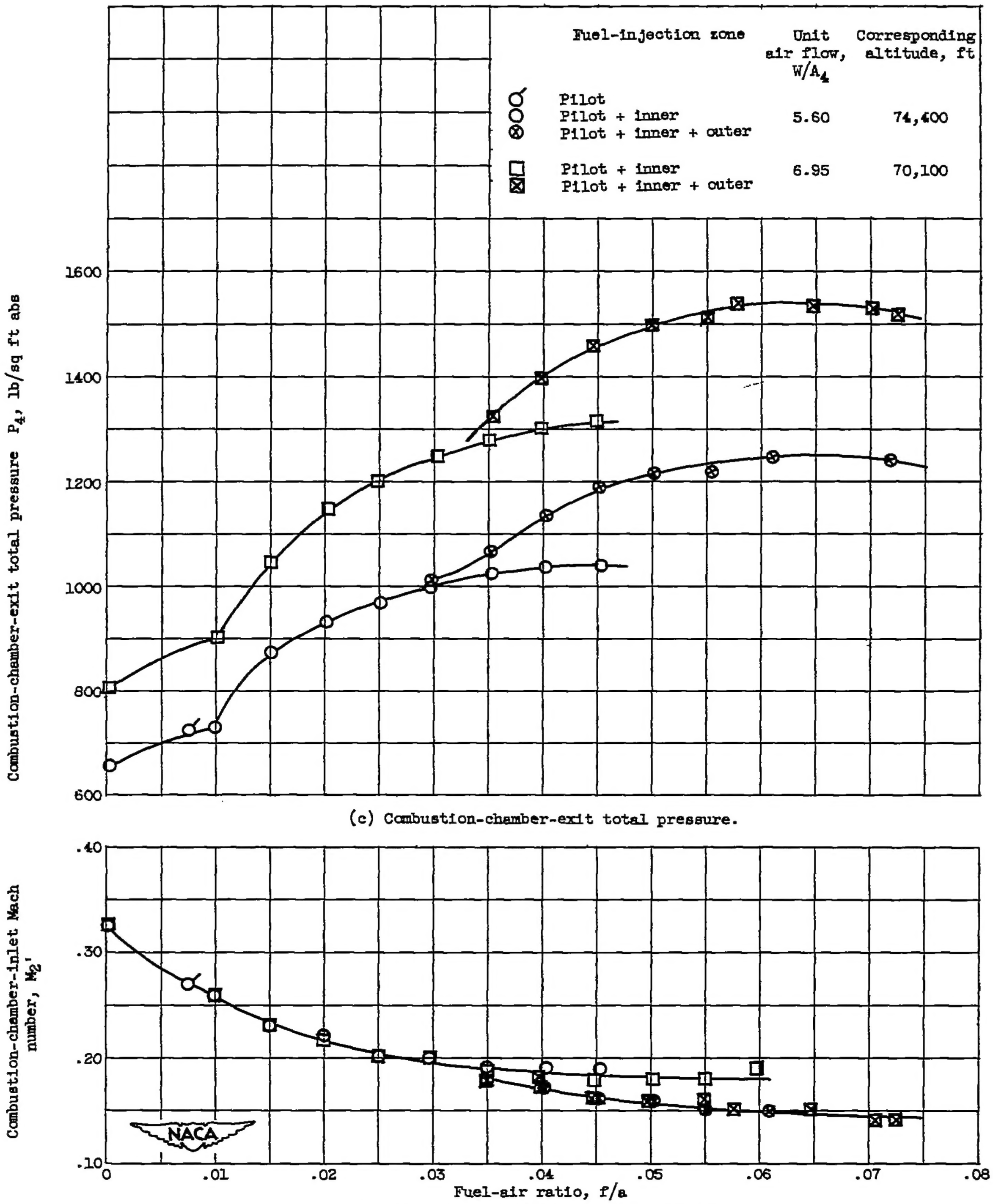

(c) Combustion-chamber-exit total pressure.

(d) Combustion-chamber-inlet Mach number.

Figure 11. - Concluded. Performance of configuration 2. High-heat-release pilot burner with sloping-gutter flame holder.

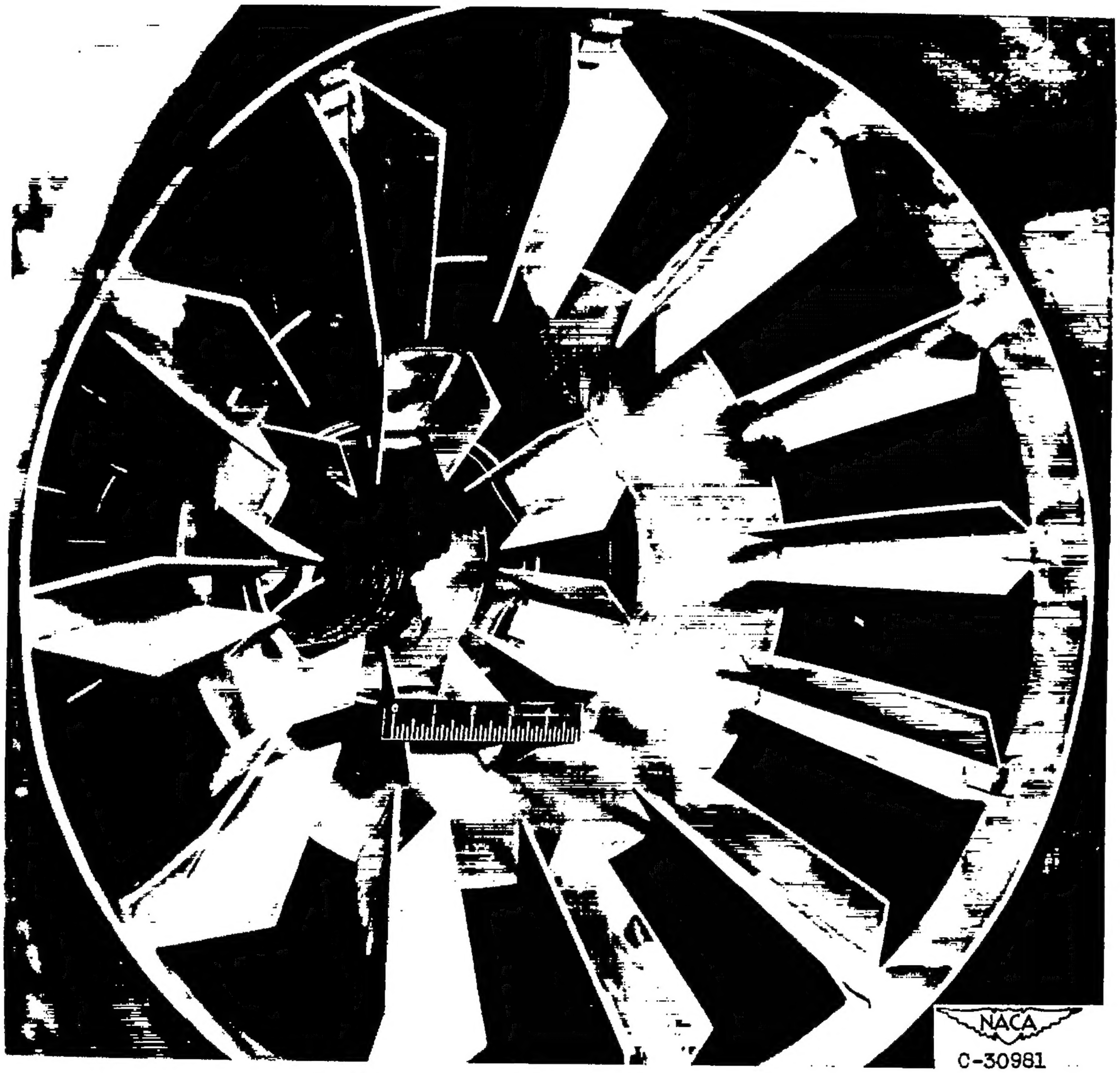

Figure 12. - Photograph of configuration 2 flame holder and pilot burner after operation.

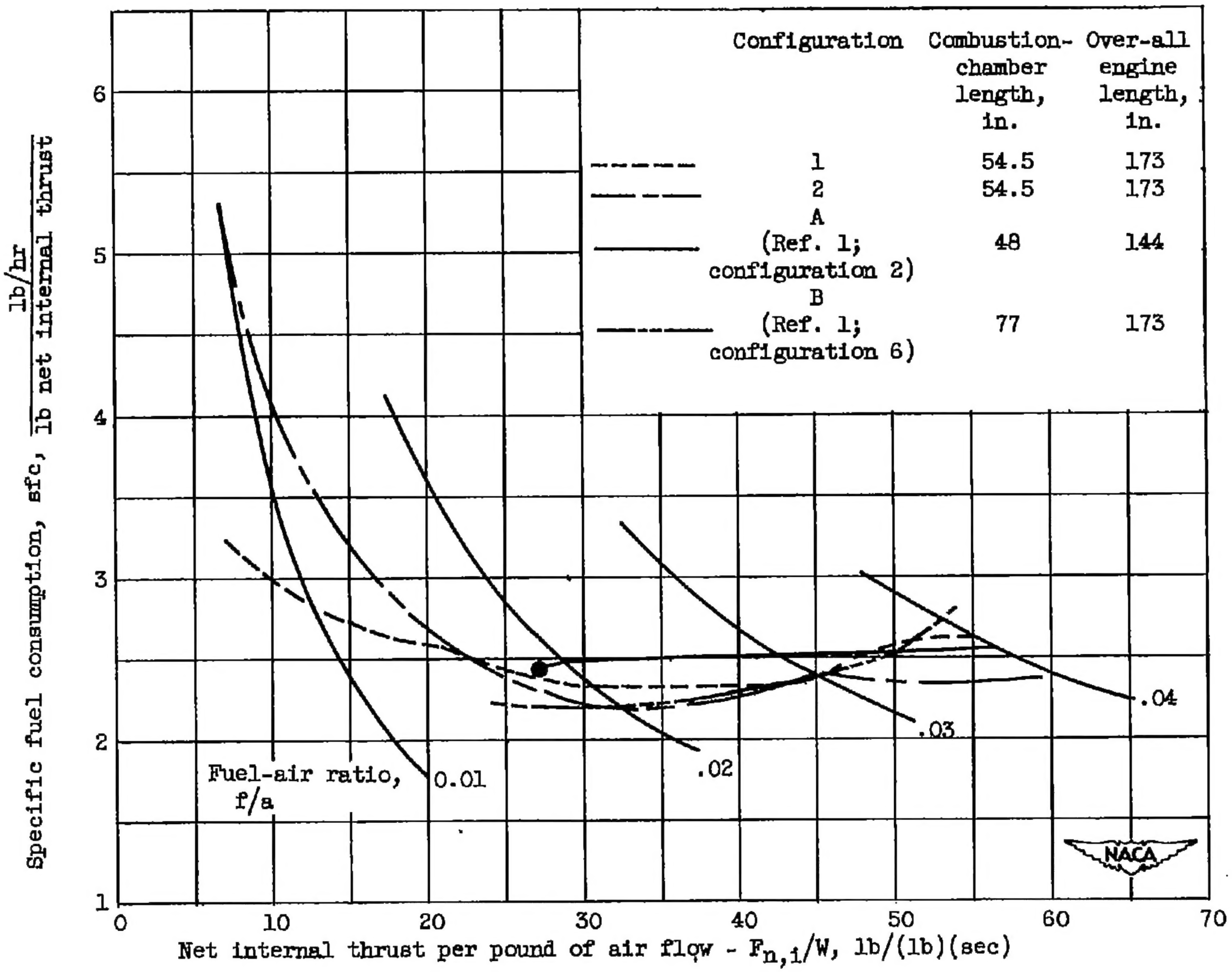

Figure 13. - Variation of specific fuel consumption with net internal thrust per pound of air flow. Diffuser total-pressure recovery, 0.6 (assumed); engine unit air flow, W/A_4, 6.93; corresponding altitude, 70,100 feet.